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THE COANDA-EFFECT OIL-WATER SEPARATOR: A FEASIBILITY STUDY

BY

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An experimental investigation which establishes the feasibility of using the Coanda-effect in developing an oil-water separator is described. Tests conducted on an experimental model with an oil-water mixture containing 6% oil showed that the oil content in the effluent can be reduced to less than 3%. A three-stage separator has produced effluent in the range of 1%. Conceptual designs of a practical separator are discussed. The space

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20. Continued.

requirement for a Coanda-effect separator when compared with typical parallel-plate type separators of the same capacity is considerably smaller. Analytical expressions useful in designing a Coanda-effect separator of a given size are also given.

INTRODUCTION

The Navy is faced with very strict regulations covering the discharge of oily wastes from its ships and shore facilities. Such wastes primarily originate from ship's bilges and ballast waters, oil spill recovery operations, fuel storage and transfer systems, and garage and maintenance activities. Technology and hardware are being developed to process such wastes so that effluent will meet EPA requirements.

Current methods of separating oil from oil-water mixtures are centrifugation, gravitation, coalescence and ultrafiltration [1,2]. Centrifugation is an accepted method for separating water-oil dispersions or emulsions [2]. Commercial equipment is available for a wide range of applications. Despite their effectiveness, the power requirement, cost and maintenance of such systems is relatively high. The gravitation method of separating oil from oily wastes relies upon differences in densities of the fluids being separated. Commercially available API and Heil type parallel separators are based upon the gravitation principle. Because of the laminar flow requirements for separation such systems are normally bulky. Coalescence has been used quite extensively for removing finely dispersed water droplets from fuels. The basic mechanism behind this separation technique is the formation of larger oil drops on the coalescing material. The resulting larger drops are separated by gravity. The method, however suffers from fouling of the coalescing element and requires frequent maintenance. Finally, ultrafiltration uses a filtering process to separate water from oil. This method, although very effective, suffers from fouling of the filter element. The system requires frequent cleaning.

A new method of separating free oil from oil-water mixtures [3] is under investigation at the Naval Civil Engineering Laboratory * (NCEL). This technique uses the fluid dynamic phenomenon, called ''wall attachment, or Coanda effect'', named after its discoverer, Henry Coanda. This effect is seen, for example, when one's finger is held close to a thin stream of water issuing from a tap or when tea is poured from a badly designed teapot-spout.

A preliminary investigation was conducted to establish the feasibility of using the Coanda effect for separating two immiscible liquids. This report describes in detail the feasibility program.

*On 1 January 1974 redesignated the Civil Engineering Laboratory (CEL) of the Naval Construction Battalion Center, Port Hueneme, California.

THEORY

Consider a thin jet sheet, quasi-two-dimensional, flowing into an unbounded region. The jet gets deflected towards an adjacent wall. When such wall is relatively close to the jet axis, the jet gets attached to and flows along the wall enclosing a separation bubble as shown in Figure 1. As is evident, the jet undergoes considerable curving during its attachment thus generating a centrifugal force field on it. This results in a lower pressure within the separation bubble. The pressure p_B in the separation bubble as derived in Appendix A is given by

$$P_\infty - p_B = J/b_o \quad \frac{3\theta}{\sigma(1/t_1^2 - 1)} \qquad (1)$$

where

P_∞ = free stream pressure,
J = jet momentum per unit span of the nozzle,
b_o = nozzle width,
θ = angular location of the reattachment point,
σ = jet spread parameter,
t_1 = $\tanh [\sigma y_1/(s_1 + s_o)]$
s_1 = axial distance between the reattachment point and the nozzle,
y_1 = half width of the jet at the reattachment point,
s_o = $\sigma b_o/3$ = distance of the nozzle exit from a hypothetical origin of the jet.

Using the theory discussed in Appendix A, dimensionless pressure $(P_\infty - p_B)\ b_o/J$ was plotted against the plate offset D/b_o for values of 7.7, 10 and 12 for the jet spread parameter σ. Figure 2 shows the pressure difference between the separation bubble and the ambient as a function of D/b_o.

For a jet composed of a mixture of two fluids which do not mix such as oil and water, the lighter fluid flowing along the plate side of the jet seeks the separation bubble and gets trapped by it. If an outlet is provided at the center of the bubble, the accumulated oil can be tapped out while the water and rest of the oil flows out of the device. This is the principle of operation of the Coanda-effect oil-water separator.

EXPERIMENTAL PROGRAM

A test program was designed to determine the feasibility of

using the wall-attachment effect in separating two liquids. Two experimental elements with different flow parameters were built and tested. The experiments were conducted in the Mechanical Systems Laboratory at NCEL using a mixture of regular tap water and hydraulic oil as the test fluid.

The Wall Attachment Elements

Based upon the theory developed in Appendix A, two experimental elements, namely, Elements No. 1 and No. 2 were designed. The 12-inch-long attachment wall of each element has an offset of 4 inches. The nozzles on Elements No. 1 and No. 2 are 1/4 and 3/8 inches wide respectively. The depth of flow passages on both elements is 1/4 inch. Element No. 1 was designed to carry 0.8 gpm of water flow whereas Element No. 2 has a flow carrying capacity of 1.5 gpm. The jet flow parameters such as reattaching distance x_R, jet center line radius r and its half width y_o at the reattachment point were determined from Figures A-2 through A-5 given in Appendix A. The jet spread parameter, σ, for the above calculations was chosen to be 12. The dimensions of the elements are listed in Table 1.

Each element consisted of three major components: top and bottom cover plates, and the middle plate with the flow passages machined in it. For ease of fabrication and to facilitate flow visualization during tests, each component plate of the Elements was made of transparent plexi-glass sheet. Further, to extract the accumulated oil in the separation bubble, a 1/4 inch diameter outlet was provided in the top cover plate of each element. The general layout showing major dimensions of the elements is given in Figure 3. The elements were assembled by gluing the two cover plates to the middle plate.

Feasibility Tests

The experiments were performed using the test setup shown in Figure 4. The adjustment of supply water flow is possible by hand controlled valves provided on the flow line. A mixture of red hydraulic oil (Appendix B) and water was used as the test-fluid. The mixture was formed by injecting the oil into water stream before it entered the element. To form a homogenous mixture, the oil was released at the center of and parallel to the water flow in the pipe. The oil to the mixing junction was supplied by a variable flow pump (see details in Appendix B). The element was immersed in water throughout the test series. The supply water flow was measured by a rotameter. The static pressure in the water line was measured by conventional pressure gauges. The use of red oil in the test mixture allowed flow visualization through the elements. The photographs of flow patterns were taken by mounting a camera directly above the elements.

The feasibility tests were conducted by running the oil

Table 1. Parameters of the Test Elements

Parameter	Element No. 1	Element No. 2
Nozzle width, b_o, inches	1/4	3/8
Wall offset, D, inches	4.0	4.0
Attachment wall length, ℓ, inches	12.0	12.0
Radius, D/b_o	16.00	10.67
Flow passage depth, h, inches	1/4	1/4
Designed water flow, gpm	0.80	1.50
Velocity at the nozzle at designed flow, feet/second	4.10	5.13
Reynold's number* at the nozzle, at designed flow	7119.7	13354.7
Jet Momentum at the nozzle, J lbs/ft	0.6794	1.595
Predicted pressure, p_B, within the separation bubble (from Figure 2) inches of H_2O	0.1978	0.3935
Predicted Attachment distance, x_R (from Figure A-5) inches	6.6	7.2
Predicted Jet center-line radius, r (from Figure A-4) inches	7.75	9.0
Predicted half width of the jet, y (from Figure A-3) inches	0.251	0.345

*Kinematic viscosity of water at 60 degrees F taken as 1.2×10^{-5} ft^2/second.

water mixture containing 6 to 8% oil by volume through the elements. The optimum water flow rates were 0.8 gpm through Element No. 1 and 1.5 gpm through Element No. 2 respectively. The mixture jet reattachment distances from the corners were measured for both elements. They were found to be 7 inches for Element No. 1 and 7.5 inches for No. 2. These values are very close to the theoretically computed values listed in Table 1. The test results indicated that a portion of the oil in the mixture jet did accumulate in the separation bubble zone of the flow. A photograph of the flow pattern (Figure 5) through Element No. 2 at its optimum flow rate clearly shows the accumulation of oil in the separation bubble. This oil when extracted contained about 50% water. Consequently, improved designs for collecting oil transferred into the separation bubble were sought. One such design is that of providing a chamber at the top of the separation bubble. This chamber is connected to the separation bubble by means of holes in the top cover plate of the element, see Figure 6. Under optimum conditions, the oil captured by the separation bubble flows into the collecting chamber through the connecting holes. Next, the oil collected in the chamber is transferred by siphoning to an oil storage tank. Two different designs of the collecting chambers were tested. These are shown in Figures 7 and 8. Due to its shape and its greater depth, the collecting chamber design shown in Figure 8 is more efficient in collecting the oil. Tests conducted on the elements with modified design show that about 50% of the oil in the input flow can be extracted in this manner, whereas the remaining oil flows out with the attached water jet. Furthermore, the oil being extracted contained about 5% water. Thus, a separating device based upon this concept appears to be capable of gross separation only. However, tests on elements with modified designs must be conducted before deriving final conclusions about the degree of separation obtainable. A photograph of the flow pattern through the Element No. 1 taken at its optimum flow rate is included as Figure 9. The accumulation of oil in the collecting chamber is clearly visible in this record.

Tests On A Multi-Stage Element

It was realized during the feasibility tests on the single-stage elements that to make the Coanda-effect separator suitable for practical applications, staging is necessary. The number of stages for the separator, however, depends upon the type of oily wastes being handled together with the quality of effluent desired.

During the course of this study a three-stage test element was designed and built to evaluate the effect of staging. Figure 10 shows the sketch of the element's middle plate with flow passages cut in it. Each stage of the element has a 1/4 inch

wide nozzle. The depth of element's flow passage was kept at 1/4 inch. The mixture jet in each stage is directed by a curved wall conforming to the curvature of a reattaching jet issuing parallel to a flat plate with an offset of 4 inches. This boundary was determined from flow governing equations given in Appendix A. The element was designed to handle 0.8 gpm of water flow through each stage. Each stage was provided with oil collecting chambers located directly on its separation bubble zone. The oil outlet line on each oil chamber was provided with a hand controlled valve for outgoing oil flow adjustment.

The element was tested using the setup shown in Figure 4. The tests were conducted by varying the oil in the mixture from 6 to 8%. The test results indicate that each stage separated about 50% of the oil from its input flow. The effluent at the third stage outlet contained about 1% oil. The oil being extracted had about 3 to 5% water. Figure 11 shows the element undergoing tests. The flow pattern through the element is shown in Figure 12. The accumulation of oil in the collecting chambers and the separated oil flowing through the outflow lines are shown in the flow record.

DISCUSSION

Jet Velocity Distribution

As mentioned earlier, the mixture jet during its attachment, develops a centrifugal acceleration. It was assumed prior to conducting the tests that the lateral acceleration so induced would force most of the oil in the jet into the separation bubble zone of the flow. The observed flow patterns through the experimental models on the other hand revealed that the oil particles were distributed uniformly over the entire cross-section of the jet. This important observation can be explained from theoretical considerations discussed in Appendix A.

Consider the reattaching jet velocity profile described by Equation 2:

$$u(s,y) = \left[\frac{3J\sigma}{4\rho(s+s_o)}\right]^{1/2} \text{Sech}^2 \frac{\sigma y}{s+s_o} \qquad (2)$$

where the various symbols are defined in Appendix A. The width of a two-dimensional jet expanding into a similar fluid at any axial location can be derived easily from a linear relationship given in References 4 and 5. The half width, y_1 of the jet is given by

$$y_1 = \left(\frac{s+s_o}{s_o}\right) b_o/2 \qquad (3)$$

It can be seen from Equation 2 that the jet velocity u(s,y) is maximum at its center-line and is

$$umax = \left[\frac{3J\sigma}{4\rho(s+s_o)}\right]^{1/2} \qquad (4)$$

Next, it can be deduced from Equations 2 and 3 that the jet velocity u(s,y) drops to 0.1814 umax at a distance equal to the half width of the jet from its center line. The centrifugal acceleration distribution in the jet can be derived from Equation 2 and is given by

$$\ddot{u}(s,y) = \frac{3J\sigma}{4\rho(s+s_o)(r\pm y)} \operatorname{sech}^4 \frac{\sigma y}{s+s_o} \qquad (5)$$

Again it is evident from Equation 4 that the centrifugal acceleration, u(s,y) is maximum at the jet center line and is

$$\ddot{u}max = \frac{3J\sigma}{4\rho(s+s_o)r} \qquad (6)$$

The acceleration drops sharply to approximately 0.0327 umax at the jet half-width points.

The typical velocity and acceleration for the reattaching jets are shown in Figure 13. Because of the nature of lateral acceleration on the jet, the oil particles are distributed over the entire cross-section. Such a distribution of centrifugal acceleration affects the separating capability of a separator with this configuration.

The mixture jet velocity and hence its centrifugal acceleration distribution can be improved by modified designs. One such design is shown in Figure 14. The device uses a splitter located at the nozzle center-line to divide the mixture jet into two sub-jets which flow along the curved walls as shown. The mixture jets flowing through the device will have velocity distribution as shown in the figure, i.e., from a maximum near the curved

walls monotonically decreasing to zero at the separation bubble center. Such a velocity distribution will induce a monotonically decreasing centrifugal acceleration on the jet with a maximum near the wall. This configuration will force most of the oil into the separation bubble. The effluent flows out through the two outlets provided on the device. Such a design should improve the separating capabilities of the separator markedly. An experimental investigation is underway to evaluate this concept.

Another possible improvement in the oil separation capability of the device can be accomplished by decreasing the static pressure within the separation bubble of the flow. This can be achieved by increasing the centrifugal force on the mixture jet which in turn can be increased by decreasing the radius of the jet center-line. The separation bubble pressure can also be decreased by increasing jet efflux momentum.

An Automated Oil Extraction System

It was observed during the feasibility tests that the rate of oil extraction from the oil collecting chambers of the elements affected the quality of oil being extracted appreciably. Too high an extraction rate disturbed the oil-water interface in the collecting chamber and the oil being extracted contained up to 50% water. A low oil extraction rate on the other hand reduced the rate of oil captured by the separation bubble of the flow. This resulted in more oil in the effluents thereby deteriorating the performance of the device. A system to control the oil extraction rate is, therefore, required for proper functioning of the separator. Such a system can be either a proportional or on-off type. Because of the simplicity of their design and their lower costs, systems of the on-off type are considered for this application.

One such system, shown in Figure 15, uses the difference in electrical conductance of water and that of the oil. Practically all oils are electrical insulators. Water (excluding pure water) is capable of conducting electricity. The system of Figure 15 uses this property in sensing the oil-water interface in the collecting chamber by providing two electrodes at different heights in it. For sensing, the electrodes are connected to a 10 volt AC supply through a 1000 ohm resistor. The solenoid valve on the outgoing oil line is operated by the output of the amplifier which receives its input from a rectified voltage signal across the resistor in the sensing circuit. The use of AC supply in the sensing circuit minimizes the electrolysis in the collecting chamber. When the oil-water interface is below the bottom electrode, the resistance in the sensing circuit is very high and practically no current flows through it.

This configuration leads to opening of the solenoid valve provided on the oil outlet line. As the oil is extracted the oil-water interface in the chamber eventually rises above the bottom electrode thereby decreasing the resistance in the sensing circuit. This results in a voltage across the resistor, which when amplified closes the solenoid valve and thus stops the oil extraction. The feasibility of the system will be determined by testing it on the experimental model of the separator.

Alternative means of sensing the oil-water interface may be employed in the foregoing control system. Use of an ultrasonic transducer, although expensive, can sense the oil-water interface precisely. Another means of sensing which can be used is based upon the photo-electric principle. Irrespective of the type of sensing used, the basic design of the control system remains unchanged.

COMPARISON WITH THE TYPICAL PARALLEL PLATE SEPARATORS

It was learned from the feasibility tests that a separating device based upon the Coanda-effect principle is capable of gross separation only. Therefore, for an evaluation the separator should be compared with typical, laminar flow parallel plate separators.

Because of its design configuration and the flow velocities through it, the Coanda-effect separator will have a considerably smaller physical size. For instance, a separator to treat 20 gpm of oil-water flow rate can be 1.5 feet long x 1 foot wide x 1.5 feet high; whereas typical parallel plate type separator [1] of the same flow capacity occupies 3 feet--3-1/2 inches x 3 feet--6 inches x 1 foot 7 inches of space. The physical size comparison of the Coanda-effect separators with typical parallel plate type separators for handling 20 and 100 fpm of mixture flow rates is given in Table 2. Because of its smaller size, for a given flow rate, the equipment cost of the Coanda-effect separator will be lower.

Presently, the Coanda-effect separator is in its early stages of development and thus many design modifications are required, therefore, a comparison of its oil separating capabilities with that of the fully developed parallel plate separator is not possible. More work is required before such a comparison can be made. Finally, because of the simplicity of its design, the maintenance of the separator promises to be easier.

Table 2. Physical Size Comparison of the Coanda Effect and Typical Parallel Plate Separators

No.	Maximum Designed Mixture Flow Through the Separator	Coanda-Effect Separator	Parallel Plate Separator
1	20 gpm	1 foot-6 inches long, 1 foot wide, and 1 foot 6 inches high	3 feet-3-1/2 inches long, 3 feet-6 inches wide, and 1 foot-7 in inches high
2	100 gpm	3 feet long, 2 feet wide, and 1 foot-6 inches high	5 feet-9 inches long, 3 feet-6 inches wide, and 3 feet-2 inches high

CONCLUSIONS AND RECOMMENDATIONS

1. The investigation conducted to date establishes the feasibility of using the Coanda effect principle in developing an oil-water separator. A separator based upon this concept will be considerably smaller than a laminar-flow separator of comparable capacity.

2. Feasibility tests conducted on an experimental model of the separator, with an oil-water mixture containing 6% oil (mixture flow rate of 1.5 gpm), show that the oil content can be reduced to less than 3%. The extracted oil contained only 5% water. To make the separator practical, staging is necessary.

3. Further, to improve the quality of extracted oil, an automated oil extraction rate controlling system is required. A concept of one such system given should be investigated by testing it on the experimental separator.

4. Improvements in the separating effectiveness of the separator can be accomplished by modifying the velocity distribution of the mixture jet to alter the centrifugal acceleration on it. A conceptual design of such a modification has been formulated.

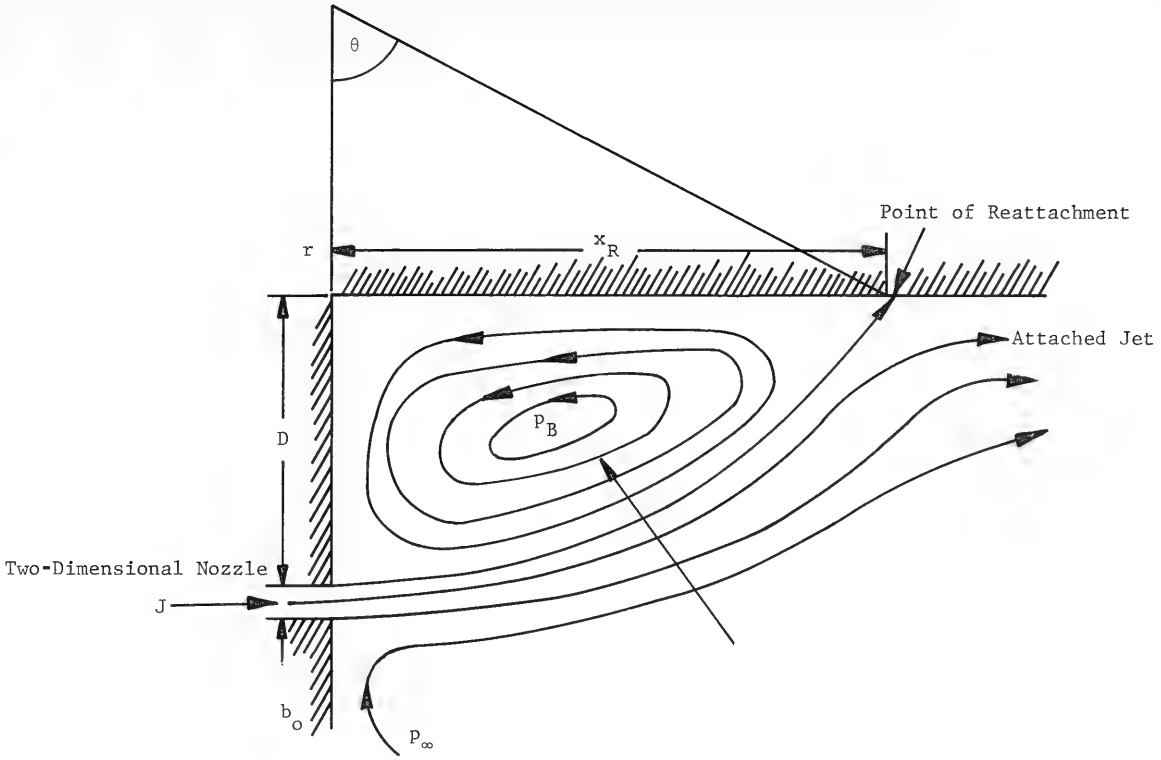


Figure 1. Two-Dimensional Jet Attaching to an Offset Parallel Plate

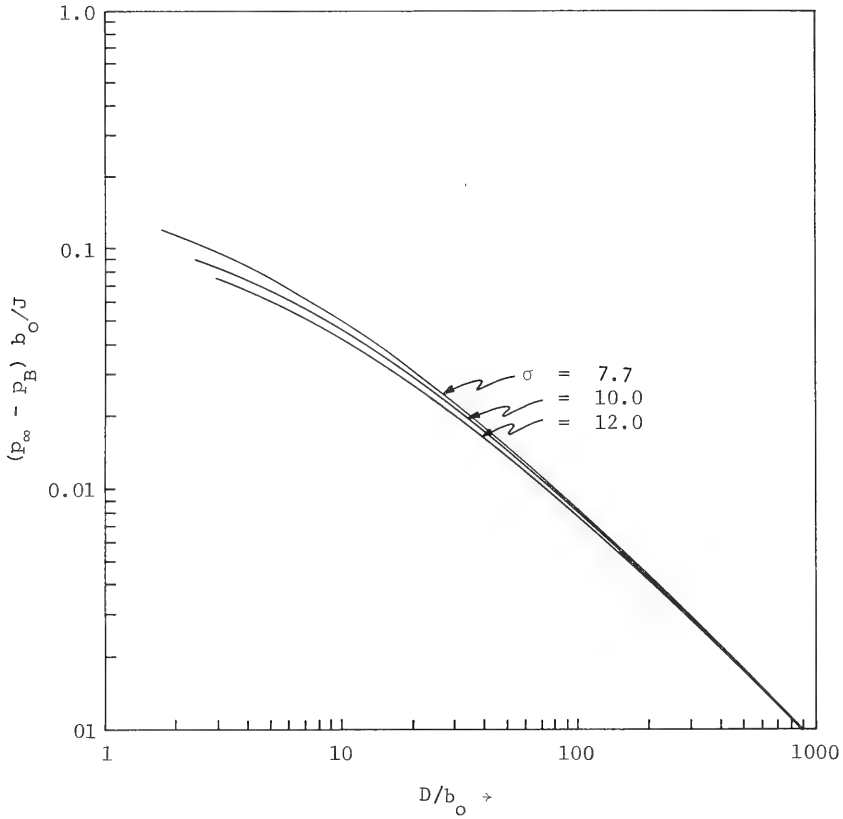
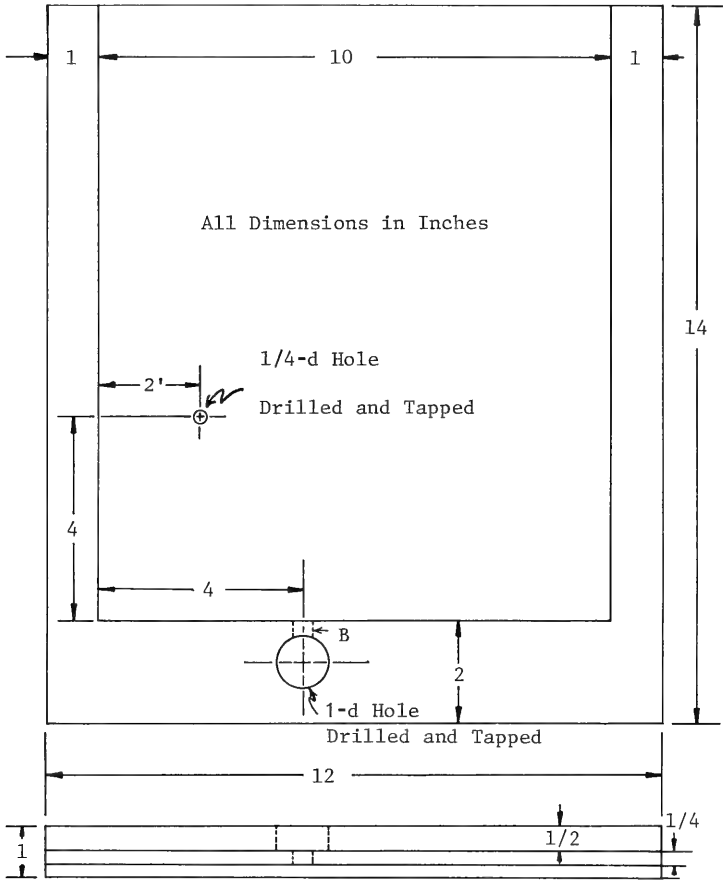


Figure 2. Dimensionless pressure $(p_\infty - p_B)b_o/J$ plotted against plate offset parameter D/b_o for various values of σ of 7.7, 10 and 12.



B is 1/4 inch for Element No. 1
B is 3/8 inch for Element No. 2

Figure 3. Sketch of the Test Element.

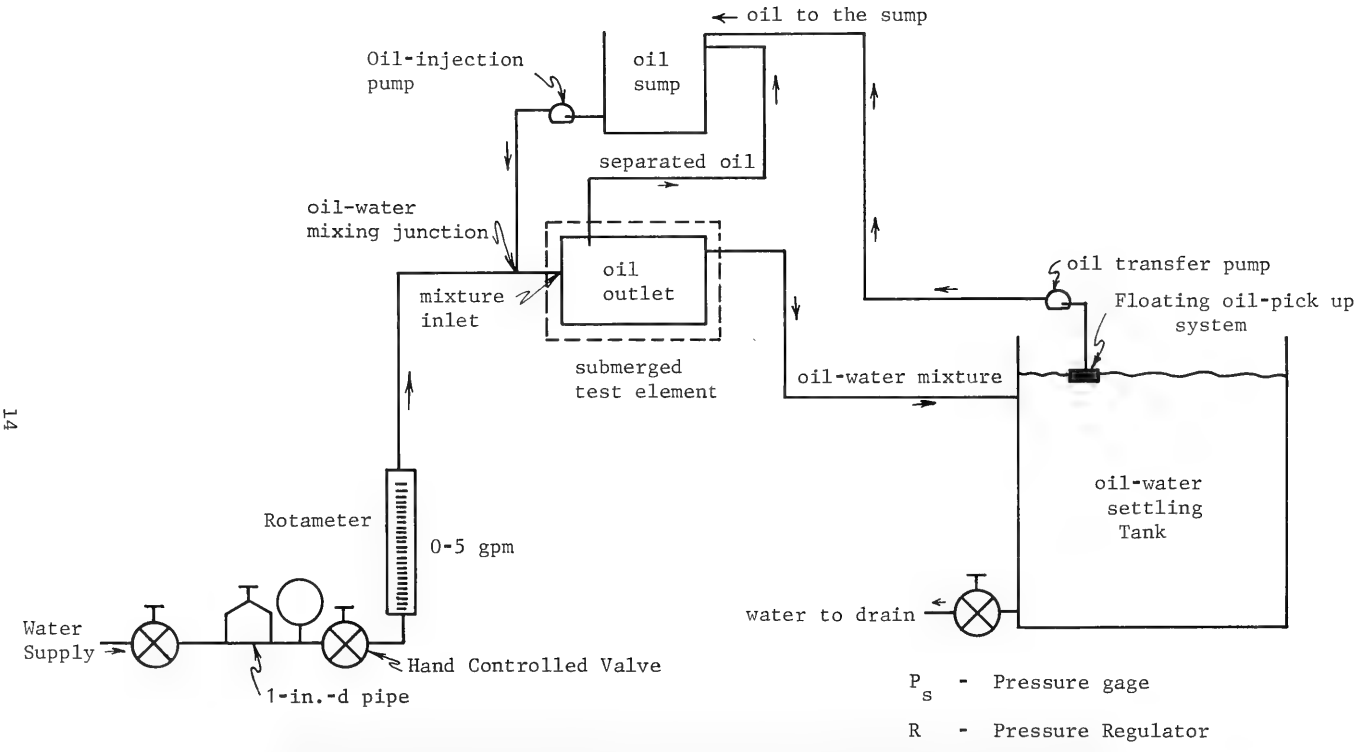


Figure 4. Schematic of the Test Setup.

Figure 5. Flow pattern through Element No. 2 at a mixture flow rate of 1.5 gpm water with 7% oil.

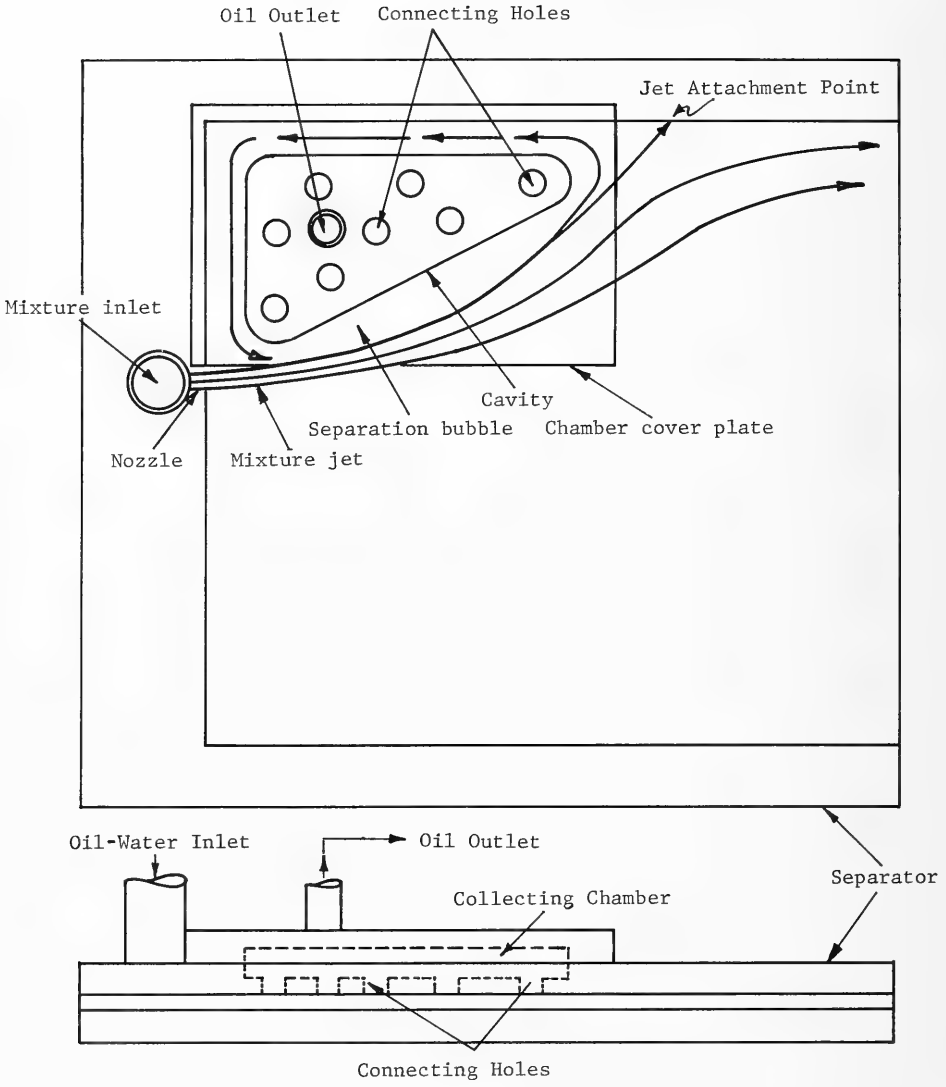


Figure 6. Single Stage Coanda Effect Oil-Water Separator Test Model.

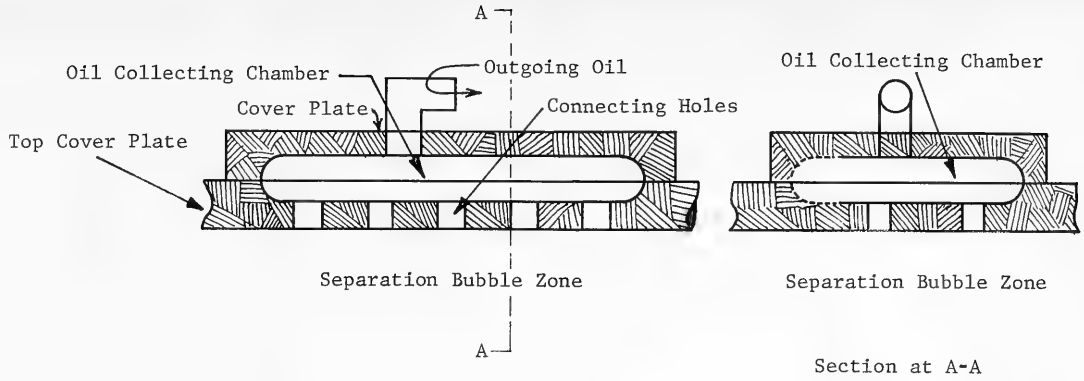


Figure 7. Design features of the oil collecting chamber.

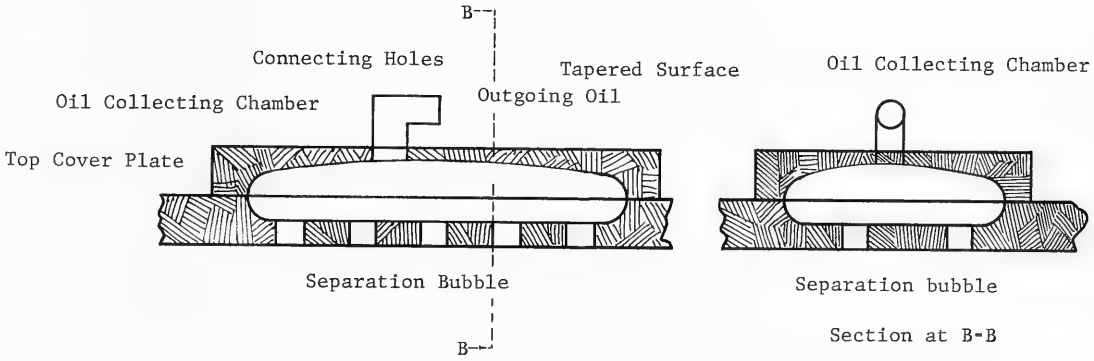


Figure 8. Modified design of the oil collecting chamber.

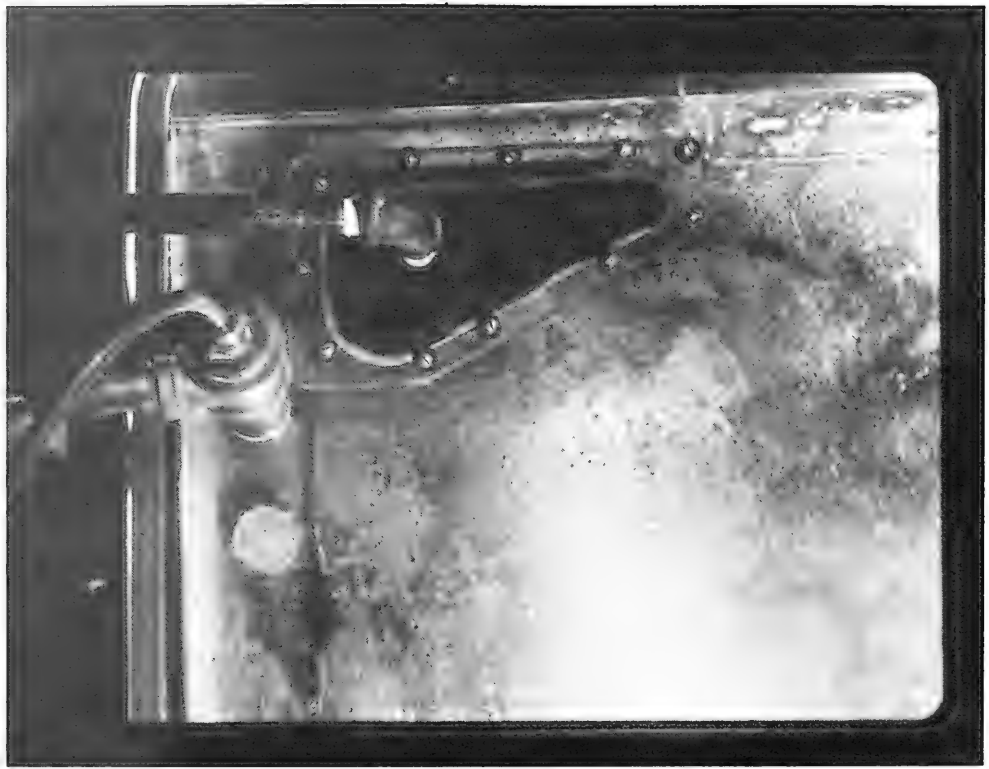
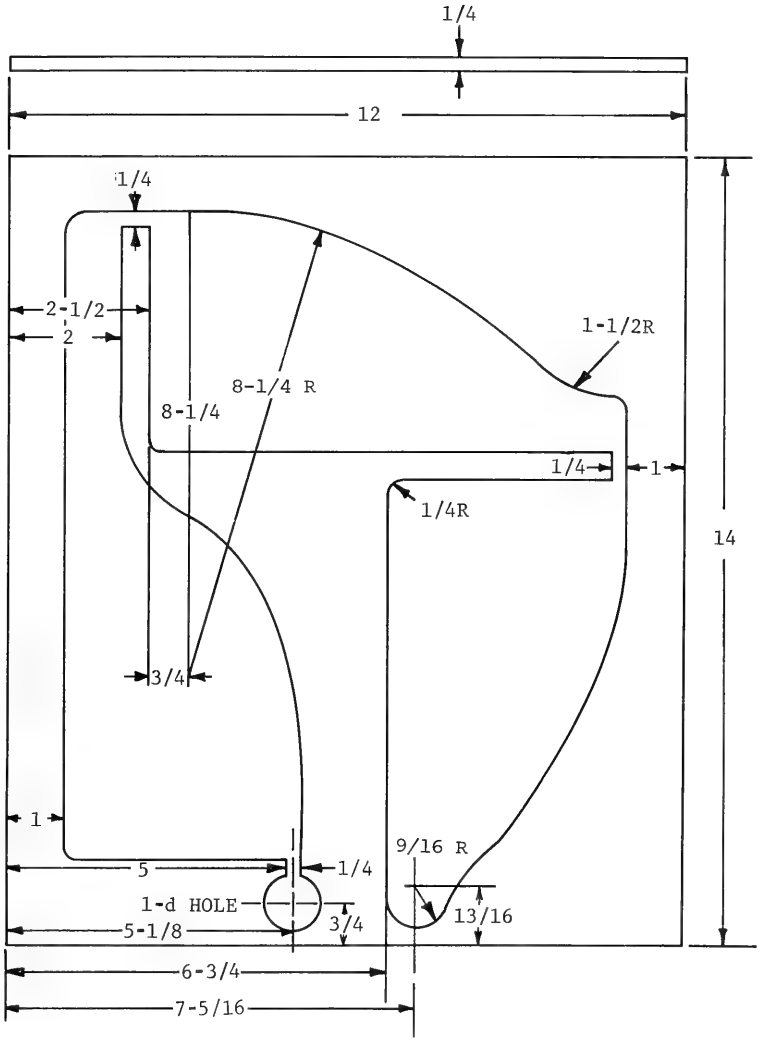


Figure 9. Flow pattern through the modified element no. 1 at 0.8 gpm water flow rate with 6% oil.



All Dimensions in Inches

Figure 10. The Sketch of Experimental 3-Stage Element

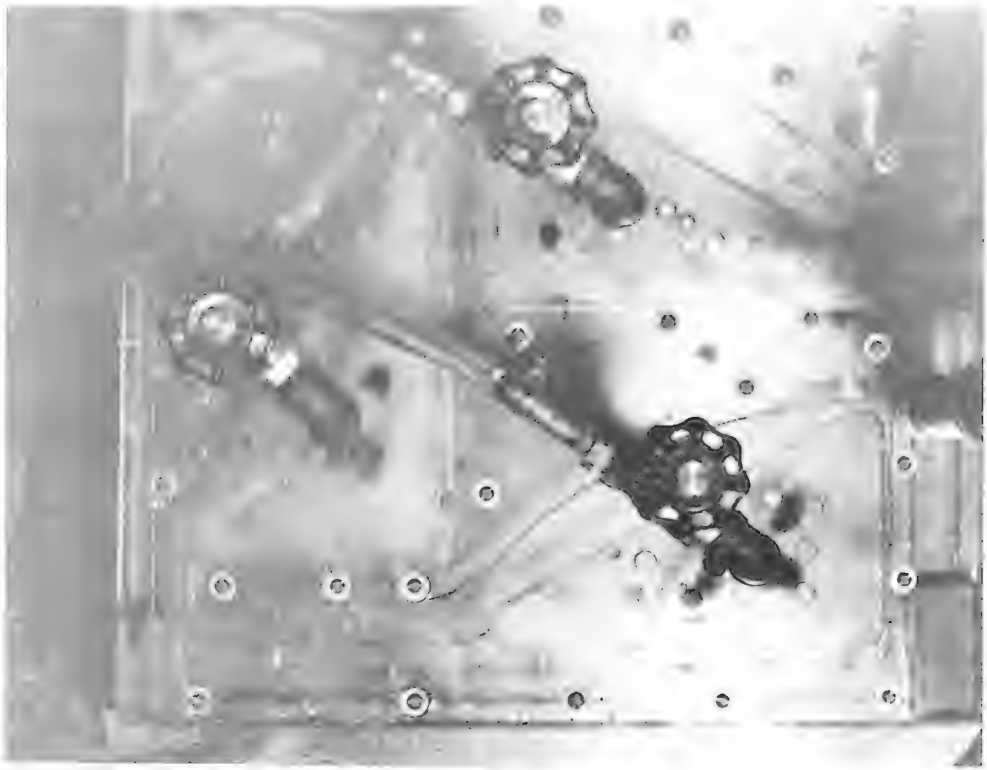


Figure 11. The three-stage test element with water flow only. The flow through device is 0.9 gpm. (The oil droplets in the collecting chambers is the residual oil from the previous tests.)

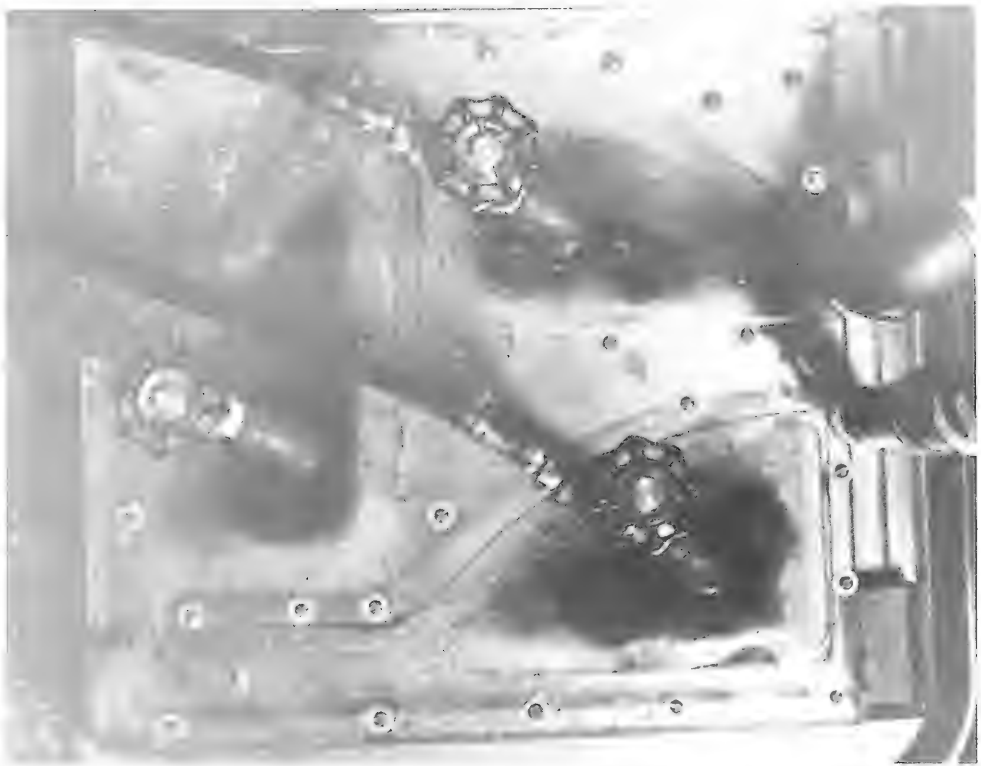


Figure 12. Flow pattern through the three stage repainting device at 0.9 gpm water flow with 6% oil.

$$u_{max} = \left[\frac{3J\sigma}{4\rho(s+s_o)} \right]^{1/2} \qquad u_{max} = \frac{3J\sigma}{4\rho(s+s_o)r}$$

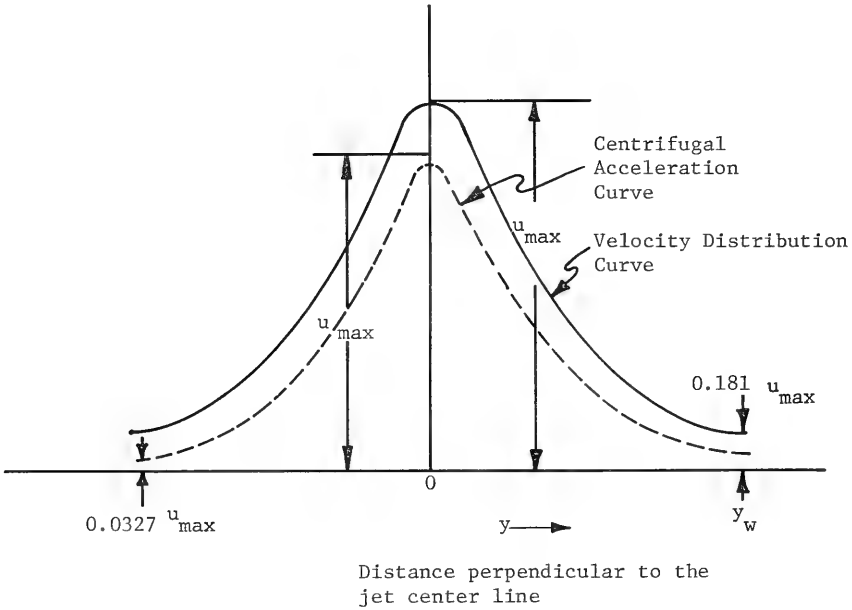


Figure 13. Reattaching Jet Axial Velocity and Centrifugal Acceleration Distributions

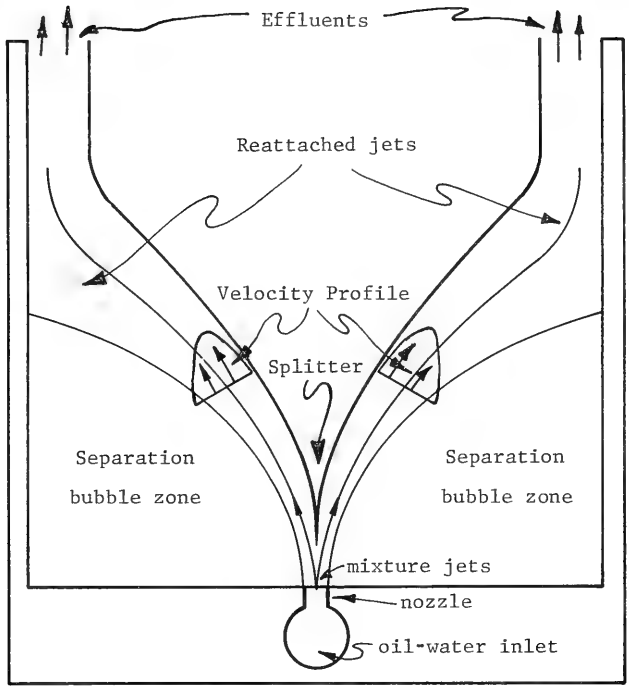


Figure 14. Conceptual Design of a Modified Separator with Improved Jet Velocity Profiles.

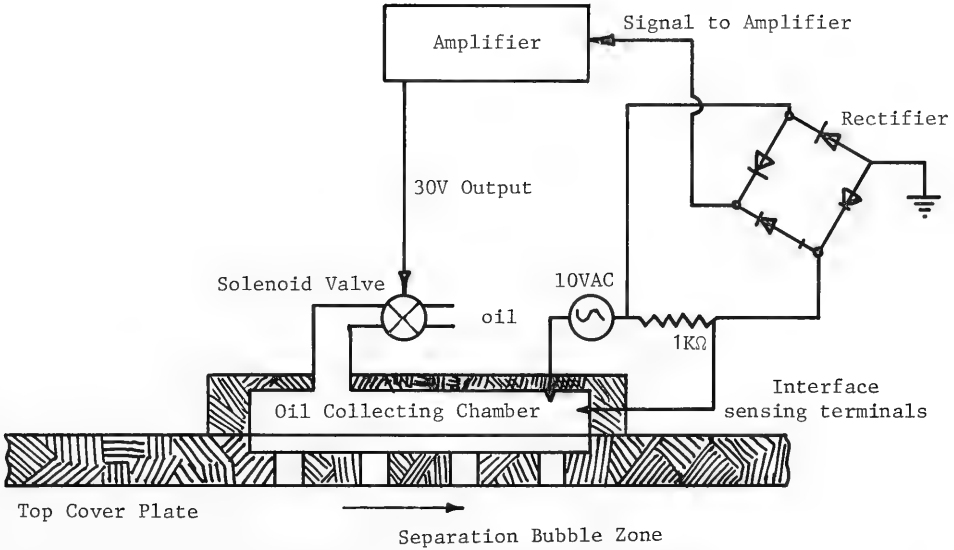


Figure 15. Schematic of an Oil Extraction System

Appendix A

EQUATIONS AND DATA DESCRIBING THE FLOW RESULTING FROM A TWO-DIMENSIONAL INCOMPRESSIBLE JET ISSUING PARALLEL TO AN OFFSET FLAT PLATE.

This appendix lists the equations and data describing the flow resulting from a two dimensional incompressible jet issuing parallel to an offset flat plate.

Wall Attachment Flow Analysis

This problem has been treated in depth by Bourque and Newman [4], and by Sawyer [5] independently. The analysis conducted by Bourque and Newman is easier to understand and covers a wide range of flow parameters. In this study therefore only the results of Reference 4 were used.

The analysis can be described by considering the flow of a two-dimensional jet issuing from a nozzle in a wall adjacent to a parallel plate with an offset D as shown in Figure A-1. The jet during its expansion entrains fluid from the surroundings by turbulent action. The entrainment of fluid from the plate side causes a pressure difference across the jet thus curving it toward the plate. If the plate is sufficiently long the jet strikes it and reattaches. The jet divides on striking the plate, sending part of the flow into the separation bubble. The flow equibilibrium is reached when the flow entrained by the plate side of the jet is equal to that into the separation bubble from the jet at the point of striking. This is the model used in the analysis of Reference 4. Further, the analysis is based upon the following assumptions:

(1) The flow is incompressible and two dimensional, i.e., only thin jet sheets are considered.
(2) The jet efflux velocity is uniform, i.e., the increase in its velocity with the reduced pressure in the separation bubble is neglected. The jet is submerged in a similar fluid and its velocity distribution is that of a free jet.
(3) The jet entrains the same amount of fluid from each boundary.
(4) Pressure within the separation bubble is constant and the jet center line is a circular arc up to the point of attachment.
(5) The force on the plate due to skin friction forces are small and are neglected.

The axial component of jet velocity used is

$$u(s,y) = \left[\frac{3J\sigma}{4\rho(s+s_o)}\right]^{\frac{1}{2}} \quad \text{Sech}^2 \quad \frac{\sigma y}{s+s_o} \qquad (2)$$

where

s = axial distance from the nozzle,
b_o = nozzle width,
s_o = distance of the nozzle from a hypothetical origin of the jet where the flow originates,
y = co-ordinate normal to the jet center line,
σ = jet spread parameter, to be determined experimentally, it has a value of 7.7 for a turbulent free jet,
$s_o = \sigma b_o/3$ (see Reference 4).

Before going any further some quantities must be defined as follows:

P_∞ = free stream pressure
p_B = Static pressure within the separation bubble
r = radius of the center line of the reattached jet,
ρ = density of the fluid,
θ = Angular location of the point of reattachment from the nozzle,
D = distance of the plate from the nozzle axis,
x_R = distance of the point of attachment from the corner,
ℓ = length of the plate
J = jet momentum per unit span of the nozzle.

The equation of the reattaching streamline is given by

$$\frac{3s}{\sigma b_o} = (1/t^2)-1 \qquad (A\text{-}1)$$

where $t = \tanh \frac{\sigma y}{s + s_o}$ (A-2)

if $t = t_1$ (A-3)

where $t_1 = \tanh \frac{\sigma y_1}{s_1+s_o}$ (A-4)

is the value of t at the point of reattachment, then the radius of the jet center line is derived from

$$r/b_o = \frac{\sigma(1/t_1^2 - 1)}{3\theta} \quad \text{(A-5)}$$

where t_1 and θ are determined from the following equations:

$$D/b_o = \frac{\sigma(1/t_1^2-1)(1-\cos\theta)}{3\theta} - \frac{1}{2} \quad \text{(A-6)}$$

and

$$\cos\theta = 3/2\ t_1 - 1/2\ t_1^3 \quad \text{(A-7)}$$

The half width of the jet at the reattachment point, i.e., y, can be easily derived from Equation A-4 and is

$$y_1/b_o = 1/3t_1^2 \tanh^{-1} t_1 \quad \text{(A-8)}$$

Further, the distance of the reattachment point from the plane of the nozzle is

$$x_R/b_o = \frac{\sigma(1/t_1^2-1)\ \sin\theta}{3\theta} - \frac{\tanh^{-1} t_1}{3t_1^2\ \sin\theta} \quad \text{(A-9)}$$

Finally, the mean pressure within the separation bubble is computed by

$$p_\infty - p_B = J/b_o \left[\frac{3\theta}{\sigma(1/t_1^2-1)}\right] \quad \text{(A-10)}$$

A wall attachment element can be designed using Equations (A-1) through (A-9).

However, to use these equations conveniently, it is required that the flow parameters x_R/b_o, r/b_o, y_1/b_o and θ be known as functions of the pre-determined parameter D/b_o. These equations are complex and can not be expressed explicitly in terms of D/b_o alone.

A numerical scheme was devised to compute x_R/b_o, r/b_o, y_1/b_o for known values of D/b_o. The numerical method runs as follows. By inspection of Equation A-7, maximum and minimum values of t_1 which render θ between 90 degrees and 30 degrees were determined. Since y_1 is positive, only positive values of r_1 must be considered. Further, it was determined from Equation A-7 that for θ to lie between 90 degrees and 30 degrees, t_1 must range between 0 and 0.50. A known value of t_1 yields θ from Equation A-7. For a selected value of σ with known t_1 and θ, parameters D/b_o, r/b_o, y_1/b_o and x_R/b_o can be determined from Equations A-6, A-5, A-8 and A-10 respectively. Thus computing a set of values for x_R/b_o r/b_o and y_1/b_o for a known D/b_o. A series of similar sets were computed by increasing t_1 by 0.05 each time up to a final value of 0.50. A total of three series of sets were computed for different θ of 12, 10 and 7.7 respectively.

For easy usage the parameters θ, y_1/b_o, r/b_o and x_R/b_o were plotted against D/b_o for values of D/b_o ranging from 1 to 1000. These plots are shown in Figures A-2 through A-5. It should be added here that flow parameters become independent of the parameter D/b_o for D/b_o greater than 35. Also the analysis becomes inaccurate for D/b_o less than 3. Further, the value of σ, , the spread parameter chosen can affect the flow parameters appreciably.

One last remark of interest is regarding the value of σ, the spread parameter to be used while using these curves. Because of the curvature effect a σ of 7.7 does not apply. It is reported in Reference 1 that a value of 12 for σ gives flow parameters values that are in fair agreement with the experimental data.

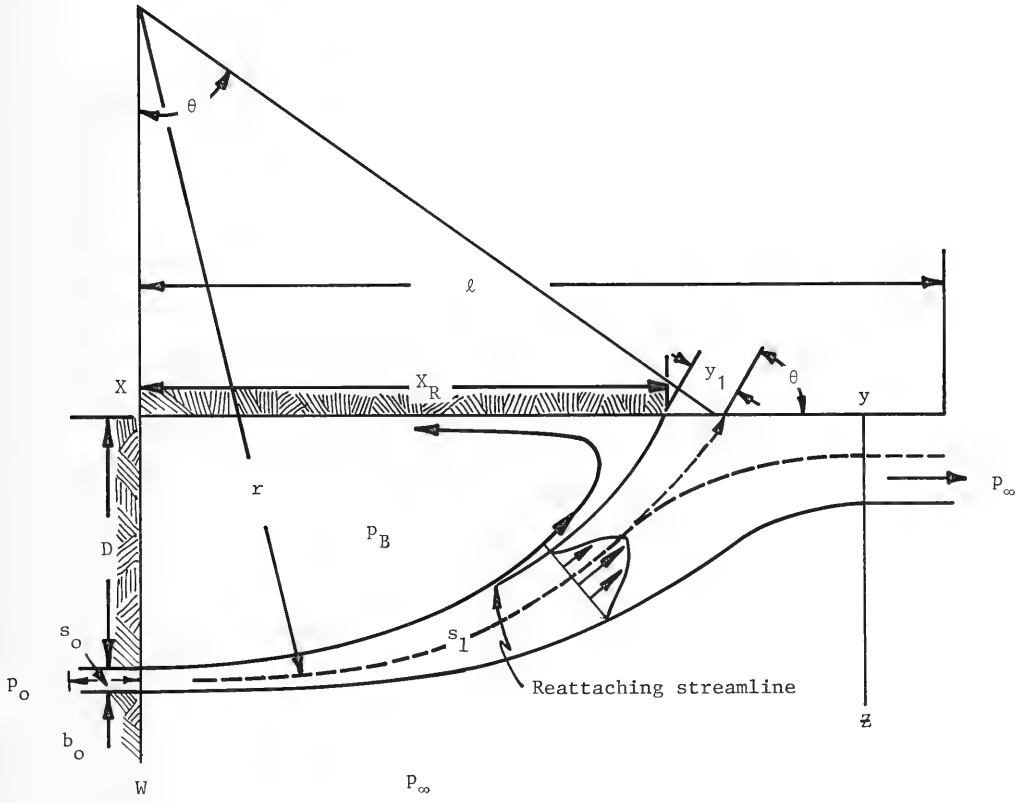


Figure A-1. A two-dimensional jet reattached to an offset parallel plate.

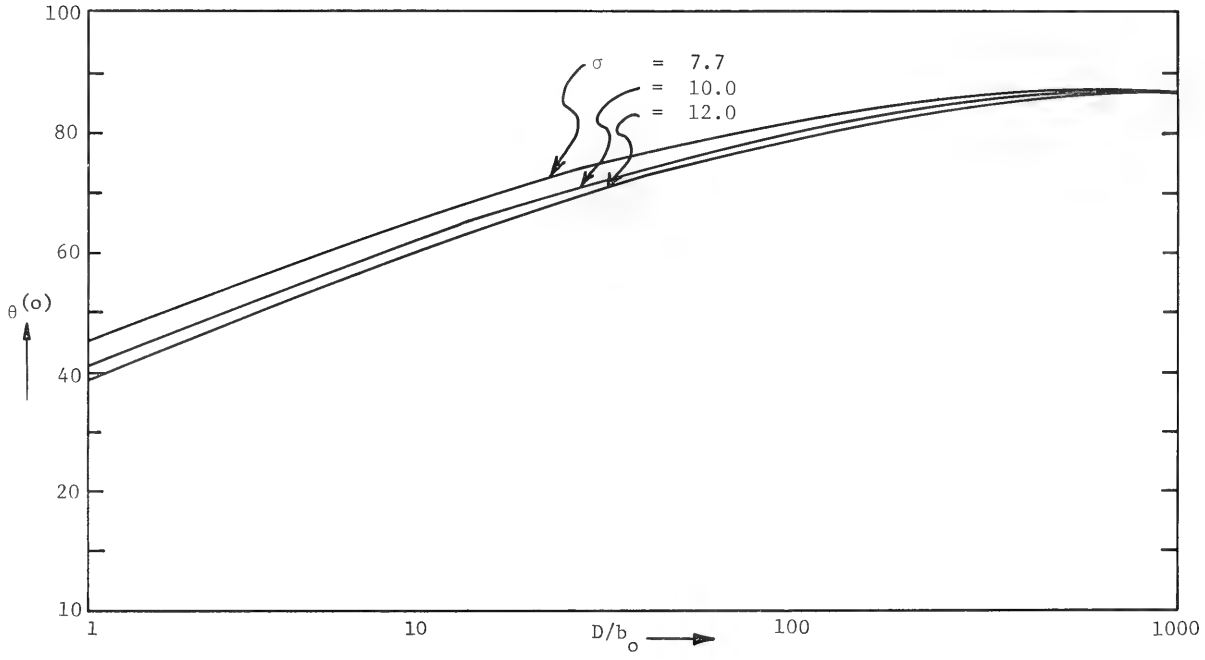


Figure A-2. Angular location (θ) of the jet reattachment point plotted against plate offset parameter D/b_o for various values of σ of 7.7, 10 and 12.

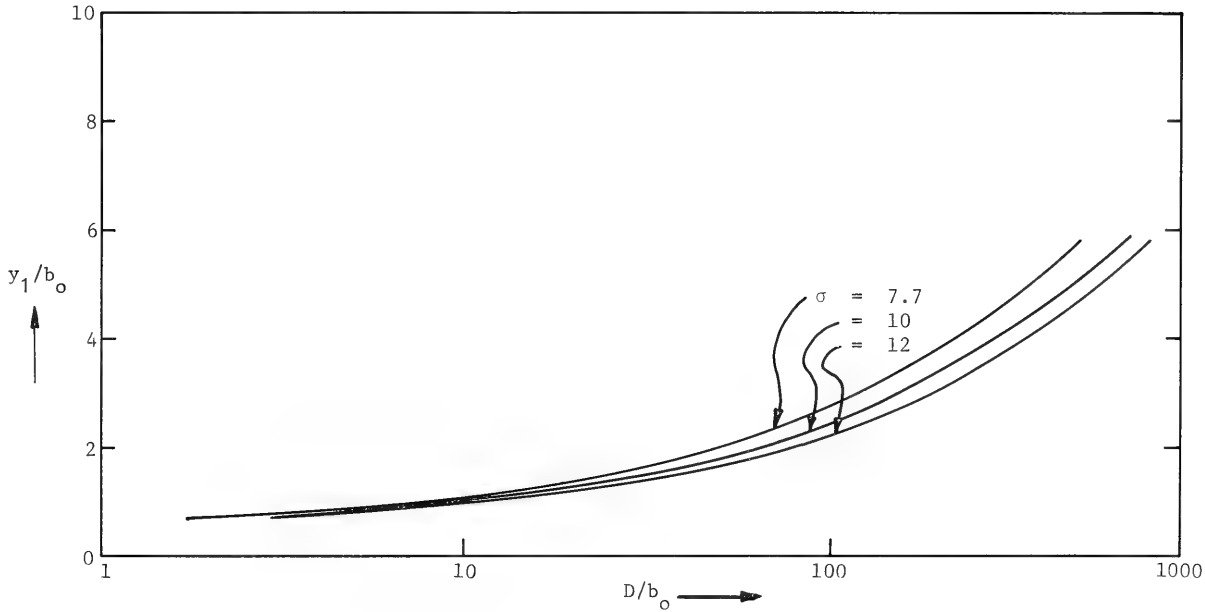


Figure A-3. Half-width (y_1/b_o) of the jet at the reattachment point plotted against plate offset parameter D/b_o for various values of σ of 7.7, 10 and 12.

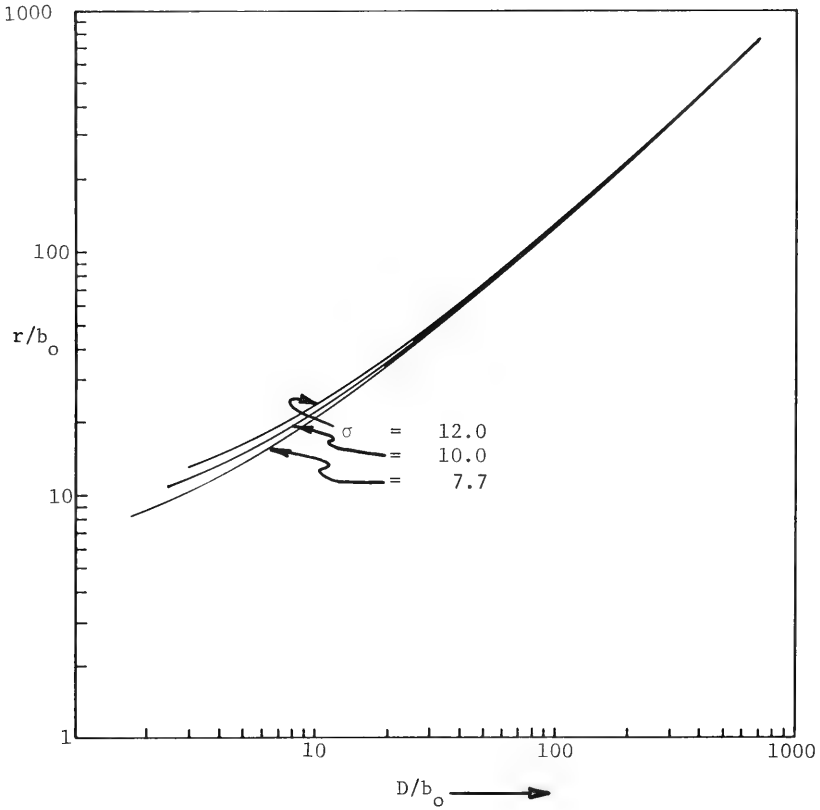


Figure A-4. Jet center line radius r/b_o plotted against plate offset D/b_o for various values of σ of 7.7, 10 and 12.

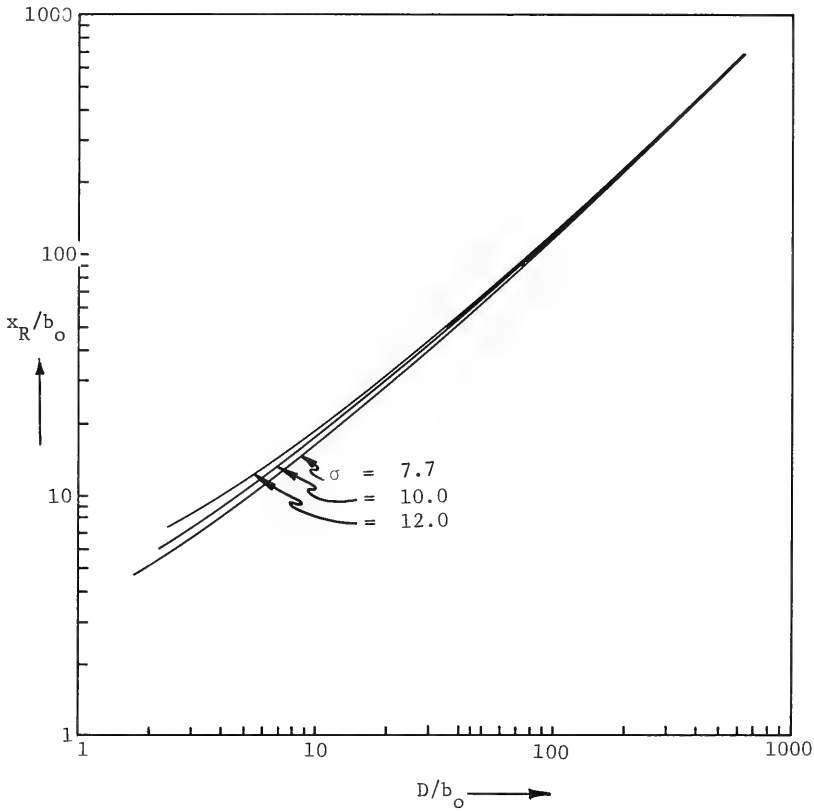


Figure A-5. Reattachment distance x_R/b_o plotted against plate offset for various values of σ of 7.7, 10 and 12.

Appendix B

SPECIFICATIONS OF OIL USED IN THE TEST MIXTURE AND THE OIL INSPECTION PUMP

This appendix lists the specification of
(a) the oil used in the test mixture
(b) the oil inspection pump

Hydraulic Fluid - Petroleum Base
Mil. spec.: MIL-H-5606C
Fed. Stock No.: FSN 9150-223-4134
Specific gravity: 0.88 to 0.90
Color: red
Kinematic viscosity: 8.0 stokes at 40 degrees F
to 0.10 stokes at 130 degrees F

Oil Injection Pump

Fluid Metering Corp
FMI Model RRP-F
with 3/8-inch piston, 0-100 cc/min at 50 psi. Variable flow with micrometer flow adjustment head. Electric motor drive. 115V, 4.5A at 60 cycles, 1725 rpm.

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